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Course of Gross Mechanical Efficiency in Handrim Wheelchair Propulsion During Rehabilitation of People With Spinal Cord Injury: A Prospective Cohort Study

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ABSTRACT. de Groot S, Dallmeijer AJ, Kilkens OJ, van Asbeck FW, Nene AV, Angenot EL, Post MW, van der Woude LH. Course of gross mechanical efficiency in handrim wheelchair propulsion during rehabilitation of people with spinal cord injury: a prospective cohort study. *Arch Phys Med Rehabil* 2005;86:1452-60.

Objective: To investigate the course of mechanical efficiency of handrim wheelchair propulsion during rehabilitation of subjects with (in)complete paraplegia and tetraplegia.

Design: Subjects were tested at the start of active rehabilitation (t_1), 3 months later (t_2), and when discharged from inpatient rehabilitation (t_3). They performed two 3-minute submaximal treadmill exercise blocks in a wheelchair.

Setting: Eight rehabilitation centers in the Netherlands.

Participants: Ninety-two people with (in)complete paraplegia and tetraplegia.

Interventions: Not applicable.

Main Outcome Measures: Mechanical efficiency values were calculated for each block. The course of mechanical efficiency was investigated using test occasions (t_1 – t_3), completeness and level (paraplegia or tetraplegia) of the lesion, and power output as independent variables in a multilevel regression analysis.

Results: Mechanical efficiency significantly increased between t_1 and t_2 only. After adding level and completeness of the lesion and their interactions with time to the model, block 2 showed that subjects with paraplegia had a significantly higher mechanical efficiency than subjects with tetraplegia. Subjects with tetraplegia improved more between t_1 and t_2 . Differences in mechanical efficiency between subjects with paraplegia and tetraplegia could not be explained by differences in absolute and relative power output levels.

Conclusions: Results showed a significant improvement in mechanical efficiency during the first 3 months of active rehabilitation. Subjects with paraplegia showed a higher mechani-

cal efficiency than did subjects with tetraplegia, whereas the latter showed more improvement between t_1 and t_2 .

Key Words: Efficiency; Rehabilitation; Spinal cord injuries; Wheelchairs.

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WHEELCHAIR PROPULSION IS a highly inefficient and strenuous mode of exercise. Gross mechanical efficiency is defined as the ratio between external power output (PO) and energy expenditure. When mechanical efficiency is calculated, values rarely exceed 10% during handrim wheelchair propulsion.¹⁻⁶ This indicates that only 10% of the internally liberated energy is used to propel the wheelchair; the rest of the energy dissipates, for example, as heat loss. The low mechanical efficiency most likely leads to a high physical strain because wheelchair users must propel the wheelchair at a higher percentage of their maximal capacity. It is important to decrease the physical strain of wheelchair propulsion in daily life to diminish the risk of overloading the user. The mechanical efficiency of wheelchair propulsion is expected to be even lower in novice patients during rehabilitation but is assumed to improve during rehabilitation. The majority of subjects with spinal cord injury (SCI) will be prepared during rehabilitation for a wheelchair-dependent mode of mobility in daily life.

Mechanical efficiency is a measure that depends on the wheelchair skills of the user⁷ and his/her training status and level of impairment.⁸ Also, the way the wheelchair is adjusted to the user (eg, seat height) or its characteristics (eg, mass) can affect mechanical efficiency.^{9,10} Improvements in mechanical efficiency during rehabilitation can be expected. Subjects probably will adapt to this completely new motor task and situation over time in different ways. First, subjects with SCI could have some recovery of functions during rehabilitation,¹¹⁻¹³ which could be beneficial for efficient performance of the task.

Second, the mechanical efficiency could change by improving the propulsion technique (eg, timing and force application). Van Kemenade et al¹⁴ investigated changes in wheelchair propulsion technique during rehabilitation of subjects with SCI between the initial stage of rehabilitation and 1 year after discharge from rehabilitation. No changes in effectiveness of force application, stroke angle, and timing parameters were detected over time, but mechanical efficiency tended to increase. It has been shown⁷ that novice able-bodied wheelchair users adapt to the new task by changing their propulsion technique (especially timing) through practice. This could relate to the significant improvement in mechanical efficiency already found after 3 weeks of practice.

Third, as a result of intensive therapies, cardiorespiratory fitness and muscular strength could improve. During rehabilitation, patients with SCI have shown a significant increase in maximal isometric strength and sprint PO. However, peak

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Table 1: Mean Values for Subjects Who Performed the Submaximal Exercise Block at a Particular Test Occasion (t_1 – t_3)

Block Characteristics	Tetraplegia t_1 (start active rehabilitation)	Paraplegia t_1 (start active rehabilitation)	<i>P</i>	Tetraplegia t_2 (3mo after t_1)	Paraplegia t_2 (3mo after t_1)	<i>P</i>	Tetraplegia t_3 (discharge from rehabilitation)	Paraplegia t_3 (discharge from rehabilitation)	<i>P</i>
Block 1									
n	16	57		18	53		25	67	
Sex (female/male)	3/13	15/42	.54	4/14	11/42	.90	4/21	19/48	.23
Age (y)	37.8±14.6	38.5±14.1	.85	35.8±13.5	38.9±14.8	.43	36.6±13.1	38.9±14.3	.41
Body mass index (kg/m ²)	23.5±5.0	23.0±3.7	.67	22.8±5.9	23.4±4.4	.70	23.7±4.8	23.8±4.8	.70
Incomplete/complete lesion	8/8	18/39	.18	8/10	15/38	.21	14/11	22/45	.04
Time since injury (d)	98±74	105±67	.71	180±42	185±76	.81	300±303	258±108	.12
PO (W)	6.7±3.0	11.8±4.8	<.001	6.5±3.5	11.8±4.5	<.001	6.9±3.6	11.7±4.6	.001
%POmax (W)	40.3±14.2	32.6±14.2	.06	35.6±13.7	26.9±12.6	.02	26.2±13.6	24.4±11.2	.37
VO ₂ (L/min)	0.64±0.12	0.71±0.15	.10	0.58±0.19	0.68±0.15	.03	0.57±0.12	0.67±0.14	.01
RER	0.86±0.07	0.88±0.08	.33	0.84±0.08	0.86±0.08	.39	0.84±0.07	0.84±0.07	.81
Heart rate (beats/min)	96±15	112±19	.002	92.6±18.2	108±15	.001	83±15	97±14	.001
Mechanical efficiency (%)	3.1±1.1	4.9±1.8	<.001	3.5±1.4	5.2±1.9	.001	3.6±1.7	5.2±1.7	.004
Block 2									
n	15	53		16	49		22	62	
Sex (female/male)	3/12	15/38	.52	4/12	10/39	.70	4/18	17/45	.39
Age (y)	35.3±14.5	38.5±14.0	.44	37.3±13.5	38.7±14.9	.73	36.8±12.7	38.3±14.4	.66
Body mass index (kg/m ²)	23.5±5.2	23.0±3.7	.68	21.4±5.1	23.1±4.7	.88	24.1±4.7	23.9±4.9	.85
Incomplete/complete lesion	8/7	16/37	<.001	8/8	14/35	.12	8/14	21/41	.02
Time since injury (d)	81±26	105±64	.16	178±44	186±76	.70	268±101	251±92	.48
PO (W)	9.8±4.1	16.5±5.6	<.001	10.2±4.0	17.0±5.3	<.001	10.4±4.4	17.0±5.4	<.001
%POmax (W)	55.8±16.6	44.8±15.1	.02	51.8±14.9	38.5±15.7	.004	38.8±16.2	33.1±12.8	.10
VO ₂ (L/min)	0.65±0.16	0.73±0.16	.09	0.61±0.21	0.75±0.15	.003	0.64±0.16	0.70±0.15	.12
RER	0.89±0.05	0.90±0.06	.60	0.85±0.08	0.88±0.07	.24	0.85±0.07	0.86±0.06	.64
Heart rate (beats/min)	98±16	115±19	.004	94±19	111±14	<.001	87±16	99±15	.001
Mechanical efficiency (%)	4.4±1.2	6.6±1.9	<.001	5.2±1.5	6.7±2.1	.01	4.9±1.7	7.2±1.8	<.001

NOTE. Values are mean ± standard deviation or as indicated. *P* values indicate the results of the independent *t* test performed for each test between subjects with tetraplegia and paraplegia.

oxygen uptake (VO₂) has not shown statistically significant improvement.¹⁵ Dallmeijer et al¹⁵ tested subjects with SCI at the initial stage of and at discharge from rehabilitation and found significant improvements in mechanical efficiency.

Within this framework, mechanical efficiency seems to be a valid measure of overall improvement in task proficiency during submaximal steady-state task performance and appears sensitive to learning and training during rehabilitation.

Other than the above-mentioned studies, no other studies have focused on changes in mechanical efficiency during the rehabilitation of people with SCI. The problem with measuring people with SCI during rehabilitation is that the subject groups are often small and heterogeneous in terms of lesion level and completeness. Our study is unique in that it included a large number (N=205) of recently injured subjects from 8 rehabilitation centers in the Netherlands and followed up with them during rehabilitation. With this many subjects, we were able to categorize them as subjects with paraplegia or tetraplegia and with complete or incomplete lesions. It has been found that people with paraplegia have a higher mechanical efficiency than those with tetraplegia.¹⁶ This could be due to differences in PO levels between the groups, because mechanical efficiency is higher when propelling at a higher PO.^{7,16} Subjects with tetraplegia will probably not be able to propel the wheelchair at the same PO as subjects with paraplegia.

Our purpose in this multicenter prospective cohort study was to evaluate the magnitude and course of mechanical efficiency during the rehabilitation of people with SCI. Our first hypothesis was that novice wheelchair-dependent subjects would adapt to the new task and consequently improve mechanical efficiency. Our second purpose was to investigate the effect of lesion level and completeness on mechanical efficiency. Our hypothesis was that subjects with paraplegia would have a higher mechanical efficiency than subjects with tetraplegia and that those with an incomplete motor lesion would show a higher mechanical efficiency than those with a complete motor

lesion. A correction for differences in PO (absolute and relative to their maximal value) between paraplegia and tetraplegia was made.

METHODS

Participants

Our study was part of the Dutch research program Physical Strain, Work Capacity and Mechanisms of Restoration of Mobility in the Rehabilitation of Persons With Spinal Cord Injuries. Subjects with recent SCI—that is, not readmissions—were recruited from 8 rehabilitation centers that specialize in SCI rehabilitation in the Netherlands. Subjects were eligible for the study if they had an acute SCI; were between 18 and 65 years of age; were classified as grade A, B, C, or D on the American Spinal Injury Association Impairment Scale; and were wheelchair dependent. Before testing, subjects were extensively screened by a physician and physical therapist. Potential participants were excluded if they had cardiorespiratory disorders described by American College of Sports Medicine guidelines,¹⁷ a resting diastolic blood pressure above 90mmHg, or a resting systolic blood pressure above 180mmHg. Subjects were also excluded if they had severe musculoskeletal problems in the upper extremities, neck, or back; had a progressive disease or psychiatric problem; or did not have enough knowledge of the Dutch language to understand the purpose of the study and the testing methods.

On the test day, subjects were asked to consume only a light meal; to refrain from smoking, drinking coffee, and drinking alcohol at least 2 hours before testing; and to void their bladders directly before testing.

Subjects were divided into 2 groups: subjects with tetraplegia (lesion level, T1 or higher) and subjects with paraplegia (lesion level, lower than T1). Group characteristics are described in table 1.

Wheelchair drag test
on a treadmill

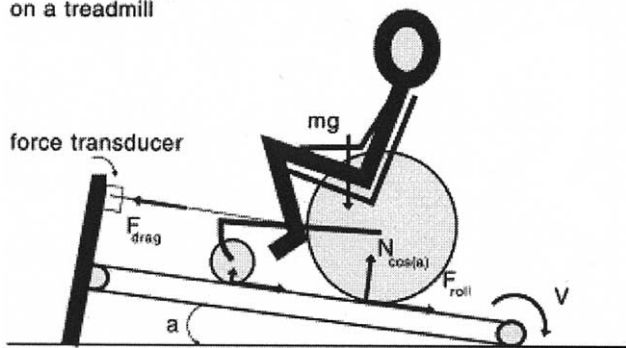


Fig 1. The wheelchair-user combination during the wheelchair drag test on the treadmill and the external forces acting on the wheelchair-user combination.

All subjects completed an informed consent form after they were given information about the testing procedure. Our Medical Ethics Committee approved all tests and protocols.

Protocol

Within the Dutch multicenter prospective cohort study, all subjects performed tests on 3 occasions during rehabilitation: at the start of active rehabilitation (t_1), 3 months later (t_2), and at the end of their clinical rehabilitation (t_3). Measurements for this study consisted of two 3-minute submaximal steady-state wheelchair exercise blocks and a maximal wheelchair exercise block on a motor-driven treadmill. Eight trained paramedical research assistants, who worked in the participating rehabilitation centers, conducted the tests. All research assistants received extensive training in how to administer the tests.

Subjects were tested in the rehabilitation centers where they were inpatients. Not all subjects completed the 3 test occasions because they were excluded because of medical complications or because they could not perform the test at the standardized test velocity.

All exercise blocks were performed in the same wheelchair model (Sopur Starlight^a with a 42×42 frame or a 46×46 frame; total mass, 11.4kg), with subject-specific adjustments of seat height, axle position, camber, and footrest height.

Velocity of the exercise blocks depended on lesion level and overall functional status. If possible, subjects with paraplegia propelled the wheelchair on the treadmill with a velocity of 1.11m/s. The velocity was set at .83m/s for subjects with a lesion level above C7 and for all subjects who could not perform the exercise block at 1.11m/s. These velocities were chosen so that the results of this study could be compared with previous research.^{15,16} Subjects who could not perform the exercise block on the 2 velocities mentioned performed the block at a velocity of .56m/s. The same test conditions were applied on all test occasions (t_1 – t_3) for each subject. When a subject was unable to perform the exercise block for 3 minutes at .56m/s, the blocks were not performed on that particular test occasion. For some subjects, 3 months after the start of active rehabilitation (t_2) was also the time of discharge from rehabilitation (t_3). Data for those subjects were recorded at t_3 , meaning that no data for those subjects were available at t_2 .

After subjects were familiarized with the testing equipment and with propelling the wheelchair on the treadmill, a drag test was performed. During that test, each subject was seated passively in the wheelchair, which was connected to a force transducer (fig 1). At a constant speed, which was the same as

the exercise velocity, the angle of the treadmill was increased with 10 steps of .36° each while the drag force was measured with the force transducer. The drag test was used to determine the rolling resistance of the wheelchair-user system on the treadmill from the force transducer data.¹⁸ PO was derived from the product of drag force and belt velocity.

After the drag test, subjects rested for 3 minutes before the first submaximal exercise block (block 1) started. Subjects propelled the wheelchair for 3 minutes with a predetermined velocity (.56, .83, or 1.11m/s) and at 0° slope. After completion of exercise block 1, subjects rested for 2 minutes before starting exercise block 2, which was performed at the same velocity but at a .36° slope. After 2 minutes of rest, the maximal test (block 3) started at the same velocity as blocks 1 and 2 and at a slope of .36°. The slope increased at a rate of .36° per minute until each subject was exhausted—that is, he/she could not propel the wheelchair at the set velocity. Exercise block 3 provided the subjects' maximal PO from which the relative PO of blocks 1 and 2 could be calculated.

Physiology

Metabolic cost was continuously measured during the exercise blocks with a metabolic cart.⁵ Calibration was performed before testing with reference gas mixtures. To obtain the gross mechanical efficiency (ME) of wheelchair propulsion, the ratio of PO to energy expenditure (En) was calculated according to

$$ME = PO_{\text{mean}} \cdot En^{-1} \cdot 100(\%) \quad (1)$$

From the measured drag force (F_{drag}) and treadmill velocity (v), the PO was calculated from

$$PO = F_{\text{drag}} \cdot v(W) \quad (2)$$

The energy expenditure was calculated from the $\dot{V}O_2$ and the respiratory exchange ratio (RER) according to Garby and Astrup¹⁹:

$$En = ([4.94 \cdot RER + 16.04] \cdot [1000 \cdot \dot{V}O_2]) / 60(W) \quad (3)$$

Energy expenditure was calculated over the last 30 seconds of exercise blocks 1 and 2.

Submaximal data were excluded from further analysis when the RER was higher than 1.05 or the PO was higher than 80% of each subject's maximal PO (%PO_{max}). These data were excluded because they did not reflect a submaximal steady-state exercise for the subject and therefore were not valid for calculating the mechanical efficiency.

Statistical Analyses

Descriptive statistics (means, standard deviations) for group characteristics and physiologic data were calculated for each exercise block and each test occasion, but only for those subjects who could perform the submaximal exercise block and who showed a valid mechanical efficiency (RER, <1.05; %PO_{max}, <80%). Furthermore, only those subjects who could perform the exercise block more than once were included in the analyses. Differences in test variables between subjects with tetraplegia and paraplegia per exercise block at each test occasion were determined using an independent t test for each test occasion ($P < .05$).

To determine whether the mechanical efficiency increases during rehabilitation, a multilevel modeling program, MLwiN,^{20,c} was used. This program is an extension of multiple regression analysis and is appropriate for analyzing hierarchically structured data. In this longitudinal data set, the hierarchy can be defined as the repeated measurement "test occasion

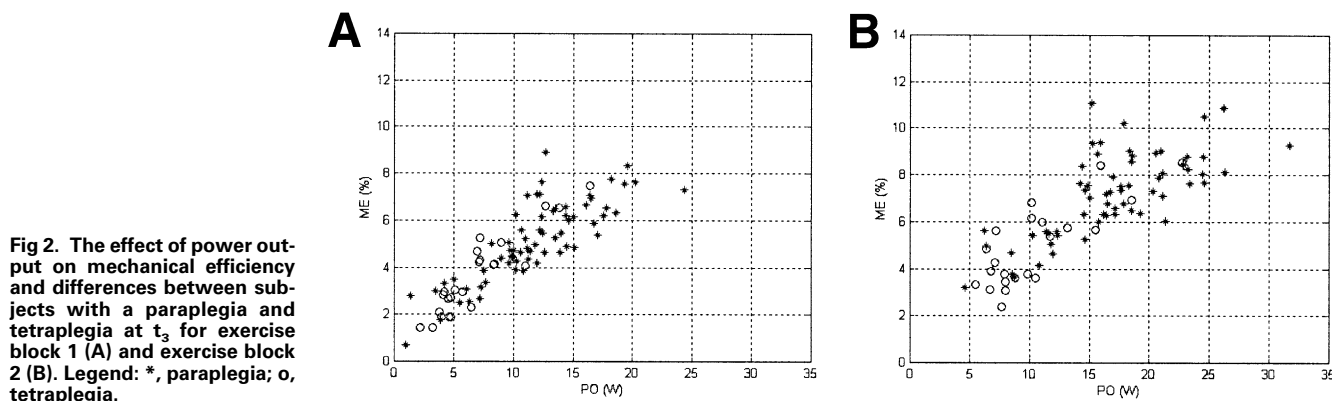


Fig 2. The effect of power output on mechanical efficiency and differences between subjects with a paraplegia and tetraplegia at t_3 for exercise block 1 (A) and exercise block 2 (B). Legend: *, paraplegia; o, tetraplegia.

(t_1 – t_3)” (level 1), which is grouped within the individual participants (level 2), who are grouped in the rehabilitation centers (level 3). The advantage of multilevel modeling is that the method considers dependency of repeated measures within the same person, and in this study, it corrected for possible differences between rehabilitation centers. Furthermore, within a multilevel analysis, both the number of observations per person and the temporal spacing of these observations may vary.²¹ Four models were built for each exercise block separately.

Model 1

An initial model was built to determine whether the mechanical efficiency changed during rehabilitation. The initial model investigated was as follows:

$$ME_{ijk} = \beta_{0ijk} + \beta_1 \cdot \Delta t_1 t_2_{ijk} + \beta_2 \cdot \Delta t_2 t_3_{ijk} \quad (4)$$

where all parameters were fixed, with the exception of the constant β_{0ijk} (intercept term), which was allowed to vary randomly at all 3 levels. Test occasions were defined as dummy variables, with t_2 as the reference. The coefficient of $\Delta t_1 t_2$ indicated the difference between t_1 and t_2 ; the coefficient of $\Delta t_2 t_3$ indicated the difference between t_2 and t_3 .

Model 2

In this model, lesion level (tetraplegia, 0; paraplegia, 1), completeness of lesion (incomplete, 0; complete, 1), and their interactions with time were added as explanatory variables. Thereafter, a backward selection was performed (removing the variable with the highest P value step by step) until only significant determinants remained.

Models 3 and 4

To investigate the influence of absolute PO or PO as a percentage of the maximal PO (%POmax) on the relation between lesion level and mechanical efficiency, PO (model 3) or %POmax (model 4) were added separately to model 2 and a backward selection was performed.

RESULTS

Descriptive Statistics

Group (paraplegia, tetraplegia) characteristics and exercise performance over the test occasions are presented in table 1. No significant differences were found between subjects with tetraplegia and paraplegia regarding age, body mass index, and time since injury. In general, more male than female subjects were included (see table 1) and the majority of the subjects had a complete lesion.

Gross mechanical efficiency was significantly higher in subjects with paraplegia than in subjects with tetraplegia at all test occasions (t_1 – t_3) and for both exercise blocks (see table 1). Subjects with paraplegia also showed a significantly higher PO than did those with tetraplegia for both exercise block 1 (on average, 11.8W vs 6.7W, respectively) and exercise block 2 (16.8W vs 10.1W) (see table 1).

The %POmax (see table 1) for each exercise block at t_1 and t_2 differed significantly between groups; subjects with tetraplegia were propelling the wheelchair at a higher %POmax during both exercise blocks than subjects with paraplegia, except at t_3 .

Figure 2 shows that mechanical efficiency increased when the external load was higher. Furthermore, it is visible that people with paraplegia propelled the wheelchair at a higher PO than did those with tetraplegia and, subsequently, at a higher mechanical efficiency. Figure 3 shows that the relation between mechanical efficiency and %POmax for subjects with tetraplegia and paraplegia is not linear.

Model 1: Course of Mechanical Efficiency During SCI Rehabilitation

Tables 2 and 3 show the results of the multilevel analyses for mechanical efficiency at exercise blocks 1 and 2. To investigate whether mechanical efficiency changed over time, time was included ($\Delta t_1 t_2$, $\Delta t_2 t_3$) as the only independent variable.

For exercise block 1, mean mechanical efficiency at t_2 was 4.8% (constant) and indicated a small but significant absolute increase of .45% during rehabilitation between t_1 and t_2 , indicated by an estimate of $-.453$ (standard error [SE]=.149) of β_1 . In contrast, no significant change in mechanical efficiency was found between test occasions 2 and 3 ($\Delta t_2 t_3$: $\beta_2=.068$, SE=.137). The same results were found for exercise block 2, where mean mechanical efficiency at t_2 was 6.5% and showed a significant absolute increase of .43% between t_1 and t_2 but no significant change between t_2 and t_3 .

Model 2: Difference in Mechanical Efficiency Between Subjects With Paraplegia and Tetraplegia

To study the effect of lesion level and completeness on the course of mechanical efficiency, these variables and their interactions with time were added to model 1. Thereafter, a backward selection was performed.

For exercise block 1, mean mechanical efficiency again showed a significant absolute increase (.46%) between t_1 and t_2 only. A significant difference in mechanical efficiency between subjects with tetraplegia and paraplegia was found; those with paraplegia showed a 1.3% higher mechanical efficiency in absolute terms. No difference in mechanical efficiency was

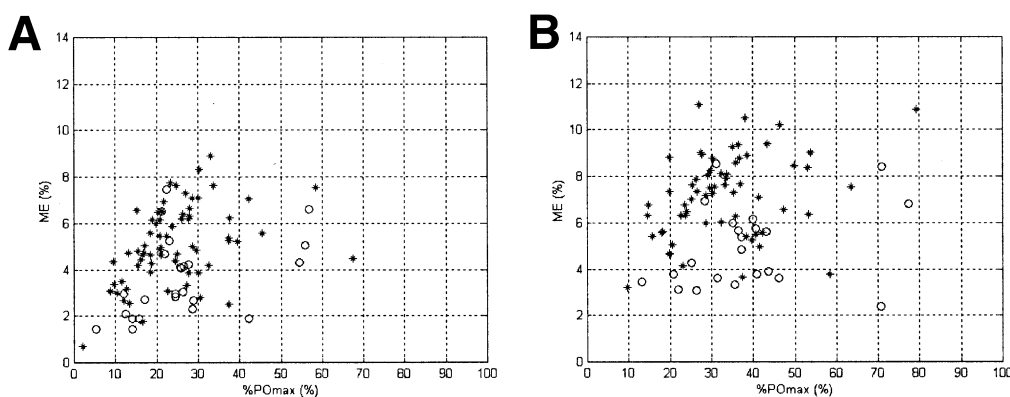


Fig 3. The effect of PO (expressed as % POmax) on mechanical efficiency and differences between subjects with a paraplegia and tetraplegia at t_3 for exercise block 1 (A) and exercise block 2 (B). Legend: *, paraplegia; o, tetraplegia.

found between subjects with a complete and incomplete lesion. Furthermore, no significant interaction between lesion level or completeness and time was found, indicating that there was no difference in course of mechanical efficiency between subjects with tetraplegia and paraplegia or subjects with a complete and incomplete lesion (fig 4).

Analysis for exercise block 2 showed a significant interaction effect between lesion level and time between t_1 and t_2 . This indicated more improvement in mechanical efficiency during the first 3 months of active rehabilitation for subjects with tetraplegia than those with paraplegia (see fig 4).

Model 3: Correction for PO

To investigate the effect of PO on the relation between lesion level and mechanical efficiency, PO was added to model 2 and a backward selection was performed. As expected, PO was a significant determinant of mechanical efficiency. PO showed a significant effect on mechanical efficiency with an absolute increase of .24% per watt (block 1) and .20% per watt (block 2). This indicates that subjects who performed at higher levels of PO on average showed a higher mechanical efficiency.

Lesion level and $\Delta t_1 t_2$ on mechanical efficiency remained in the regression model for exercise block 1. For exercise block 2, the interaction lesion level $\cdot \Delta t_1 t_2$ showed a significant effect on mechanical efficiency. This indicated more improvement in mechanical efficiency for subjects with tetraplegia compared

with those with paraplegia between t_1 and t_2 after correcting for differences in PO levels between the groups.

Model 4: Correction for %POmax

Because there also was a significant difference in %POmax between subjects with paraplegia and tetraplegia—that is, subjects with tetraplegia performed the exercise blocks at a higher %POmax—this variable was added to model 2 to correct for that difference.

The %POmax remained in the regression model for exercise block 1. After correcting for differences in %POmax between the lesion groups, lesion level still showed a significant effect on mechanical efficiency.

The %POmax had no significant effect on mechanical efficiency for exercise block 2 and, therefore, was removed from the model.

DISCUSSION

Course of Mechanical Efficiency During SCI Rehabilitation

The multilevel modeling technique we used has provided insight into the longitudinal course of mechanical efficiency during rehabilitation of people with SCI. It should be kept in mind that the subjects studied were a positive selection from a

Table 2: Multilevel Regression Analysis for Mechanical Efficiency With 3 Levels (3, center; 2, subject; 1, occasion) for Exercise Block 1

Parameter	Model 1 β (SE) (basic)	P	Model 2 β (SE)	P	Model 3 β (SE)	P	Model 4 β (SE)	P
Fixed								
Constant	4.774 (0.518)		3.788 (0.511)		1.954 (0.301)		3.202 (0.516)	
$\Delta t_1 t_2$	-0.453 (0.149)	.002	-0.459 (0.148)	.002	-0.364 (0.126)	.004	-0.581 (0.153)	<.001
$\Delta t_2 t_3$	-0.068 (0.137)	.62	-0.050 (0.137)	.72	-0.039 (0.118)	.74	-0.007 (0.139)	.96
Lesion	-		1.287 (0.200)	<.001	0.390 (0.161)	.02	1.395 (0.203)	<.001
Completeness	-		NS		NS		NS	
Lesion $\times \Delta t_1 t_2$	-		NS		NS		NS	
Lesion $\times \Delta t_2 t_3$	-		NS		NS		NS	
Completeness $\times \Delta t_1 t_2$	-		NS		NS		NS	
Completeness $\times \Delta t_2 t_3$	-		NS		NS		NS	
Power output	-		-		0.241 (0.019)	<.001	-	
%POmax	-		-		-		0.018 (0.007)	.01

NOTE. $\Delta t_1 t_2$ and $\Delta t_2 t_3$ are the dummy variables for the measurement times to indicate possible changes over time. β is the regression coefficient.

Abbreviation: NS, not significant.

Legend: 0, incomplete; 1, complete; 0, tetraplegic; 1, paraplegic; -, not entered in the model.

Table 3: Multilevel Regression Analysis for Mechanical Efficiency With 3 Levels (3, center; 2, subject; 1, trial) for Exercise Block 2

Parameter	Model 1 (basic) β (SE)	P	Model 2 β (SE)	P	Model 3 β (SE)	P	Model 4 β (SE)	P
Fixed								
Constant	6.493 (0.537)		5.701 (0.579)		3.351 (0.442)		5.701 (0.579)	
$\Delta t_1 t_2$	-0.428 (0.193)	.03	-1.394 (0.401)	<.001	-1.015 (0.352)	.004	-1.394 (0.401)	<.001
$\Delta t_2 t_3$	0.171 (0.180)	.34	-0.276 (0.358)	.44	-0.277 (0.314)	.38	-0.276 (0.358)	.44
Lesion	-		1.026 (0.359)	.004	0.076 (0.320)	.81	1.026 (0.359)	.004
Completeness	-		NS		NS		N.S.	
Lesion $\times \Delta t_1 t_2$	-		1.262 (0.455)	.006	0.974 (0.399)	.01	1.262 (0.455)	.006
Lesion $\times \Delta t_2 t_3$	-		0.642 (0.416)	.12	0.651 (0.365)	.07	0.642 (0.416)	.12
Completeness $\times \Delta t_1 t_2$	-		NS		NS		NS	
Completeness $\times \Delta t_2 t_3$	-		NS		NS		NS	
Power output	-		-		0.198 (0.020)	<.001	-	
%POmax	-		-		-		NS	

NOTE. $\Delta t_1 t_2$ and $\Delta t_2 t_3$ are the dummy variables for the measurement times to indicate possible changes over time. Legend: 0, incomplete; 1, complete; 0, tetraplegic; 1, paraplegic; -, not entered in the model.

complete database of the prospective cohort study. For example, at t_1 only 20% and 49% of all subjects with tetraplegia and paraplegia, respectively, were able to perform the exercise blocks.

Mechanical efficiency showed a significant increase over time in all subjects as a group, with a significant improvement of .45% during the first 3 months of active rehabilitation for exercise block 1. Mechanical efficiency did not change significantly after those 3 months of rehabilitation until time of discharge.

Dallmeijer et al¹⁵ studied the physical performance during rehabilitation of subjects with recent SCI and also found a significant improvement in mechanical efficiency during rehabilitation. The Dallmeijer¹⁵ study was extended to investigate the course of mechanical efficiency between the initial stage of rehabilitation and 1 year after discharge from rehabilitation.¹⁴ Mechanical efficiency had a tendency to increase. It seemed that mechanical efficiency improved during rehabilitation but not by much after discharge. From the results of this study, it can be concluded that mechanical efficiency mainly increased during the first 3 months of rehabilitation. It has been suggested²² that novices learn wheelchair propulsion rather quickly in the beginning and that performance levels off after a few months. This might be due to more intensive (wheelchair) training in the beginning of active rehabilitation compared with

the last part. The practice period between t_1 and t_2 (average, 80–100d) was in general less than that between t_2 and t_3 (average, 75–120d). Because the test occasions were defined as (dichotomous) dummy variables, the exact practice periods—in terms of days—were not taken into account. There was a lot of variation in the time since injury between the subjects at the different test occasions.

Differences in Mechanical Efficiency Between Subjects With Paraplegia and Tetraplegia

Both above-mentioned studies^{14,15} included people with paraplegia and tetraplegia as 1 group. The level of the lesion is in general an important determinant of a person's physical capacity and mechanical efficiency. Studies have shown that subjects with high-level injuries have lower physical capacity levels and lower mechanical efficiencies than those with low-level injuries.^{16,23} Therefore, it could be expected that people with tetraplegia have a lower mechanical efficiency than those with paraplegia. When adding lesion level and completeness to the basic regression model, it was found that lesion level had a significant effect on mechanical efficiency; subjects with paraplegia showed a significantly higher mechanical efficiency than subjects with tetraplegia. That could be partly explained by the fact that subjects with paraplegia were able to perform the exercise blocks at a higher PO than were subjects with tetraplegia. The latter group will—because of extensive loss in active muscle mass and function—not only have a much more limited cardiorespiratory capacity but also further reduced trunk and arm muscle function. Loss of arm function in people with tetraplegia will not only limit the ability to generate external arm-hand muscle power but also affect its coordination.

The models of block 2, with or without correcting for PO, showed a significant difference between subjects with tetraplegia and paraplegia in the change over time in mechanical efficiency (see fig 4). Subjects with tetraplegia showed more improvement in mechanical efficiency during the first 3 months of rehabilitation than did the subjects with paraplegia. Although subjects with paraplegia and tetraplegia must learn wheelchair propulsion from scratch during rehabilitation, subjects with tetraplegia also must learn how to coordinate their arms again because of loss of functioning of some arm and shoulder muscles. Our results suggest that subjects with tetraplegia seemed to adapt mainly to the new coordination pattern of their arms and to handrim wheelchair propulsion within the first 3 months of rehabilitation.

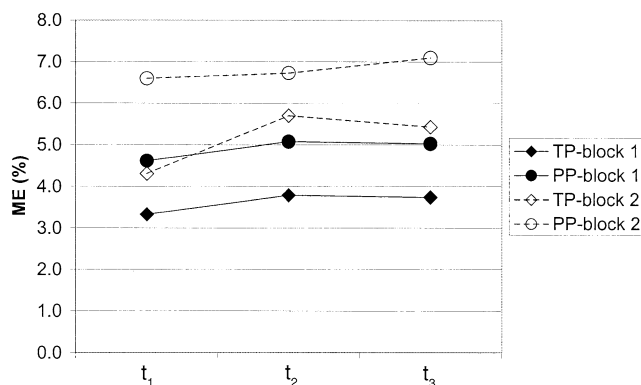


Fig 4. Results of the multilevel analyses for exercise blocks 1 and 2 to describe the course of mechanical efficiency (ME) during rehabilitation for subjects with tetraplegia (TP) and paraplegia (PP).

Differences in Mechanical Efficiency Between Subjects With Complete and Incomplete Lesions

No significant difference in mechanical efficiency was found between subjects with a complete or incomplete motor lesion regardless of correction for differences in PO or %POMax. This was a remarkable result, because it could be expected that subjects with an incomplete high lesion would have fewer difficulties in performing wheelchair propulsion tasks because functional loss to the trunk and upper extremities is less apparent. That no effect of completeness was found might be due to the relative low number of subjects with incomplete tetraplegia. Subjects with incomplete paraplegia will have more muscle functions in their legs, which in itself is highly relevant in rehabilitation but would probably have no critical influence on the ability to propel a handrim wheelchair and thus on the accompanying mechanical efficiency. Moreover, subjects with an incomplete lesion were only included when they were wheelchair dependent, which means that they also had severe damage of the spinal cord, an indication of the specific subject selection studied here.

Correction for PO and %POMax

Previously it was found that subjects, able-bodied as well as those with SCI, show a higher mechanical efficiency when performing the exercise block at a higher level of PO.^{7,16,24,25} Gross mechanical efficiency includes not only the metabolic power to generate the amount of external mechanical PO but also the metabolic power needed for basal processes such as ventilation and trunk stabilization.²⁶ When external mechanical PO increases, the relative contribution of the basal metabolic power (E_b in formula 1) to the total metabolic power (E_b plus PO needed to perform the task [E_{task}]) will diminish as it becomes proportionally less, leading to a higher gross mechanical efficiency with increments in PO^{24,27}: $(ME = PO / (E_b + E_{task}))^{-1} \cdot 100\%$. The association between mechanical efficiency and PO is typically curvilinear, showing an initial increase that flattens off at upper levels of submaximal PO, where mechanical efficiency is generally highest.²⁸ Because subjects with paraplegia systematically performed at a higher PO than those with tetraplegia, it was expected that after correcting for the different levels of PO values found between subjects with tetraplegia and paraplegia, the effect of lesion level on mechanical efficiency would diminish. The results indeed showed that mechanical efficiency was significantly dependent on PO. Still, a lower mechanical efficiency in subjects with tetraplegia was found, which might be due to their limited ability to optimally coordinate their upper extremities compared with subjects with paraplegia.

It was also expected that subjects with tetraplegia were propelling the wheelchair—at least initially—at a higher percentage of their POMax than were subjects with paraplegia, which also could have a different effect on mechanical efficiency between the lesion groups. Table 1 shows that people with tetraplegia propelled the wheelchair at a significantly higher %POMax than did those with paraplegia, except at t_3 . When adding %POMax to the model instead of PO, it was found that %POMax was a determinant for mechanical efficiency in exercise block 1 but not in block 2. Figure 3 also shows that the relation between mechanical efficiency and %POMax was not linear.

Limitations and Implications

Subjects were tested the first time at the start of active rehabilitation (when they were able to sit for 3h), which was on average 81 to 105 days after injury. This means that a subject

could have had some wheelchair experience before the first test occasion.

The improvement in mechanical efficiency might even be more had the subjects been tested in their own wheelchairs. Because a subject's personal wheelchair is often changed during rehabilitation, we decided to use a standardized test wheelchair for every test. Although the test wheelchair was adjusted and there was a familiarization period, most subjects preferred their own wheelchairs. The test results might, therefore, show less improvement than a subject's actual improvement when using his/her own chair. This effect will be more dominant with time because at the end of rehabilitation the subjects will be used to their own wheelchair, in contrast to the beginning of rehabilitation. This could also explain part of the absence of an increase between t_2 and t_3 .

The changes in mechanical efficiency over time were quite small in absolute terms, with a maximum increase of 1.4% between t_1 and t_2 for subjects with tetraplegia. However, this was a relative increase of 32%. The effect of this 1.4% increase in mechanical efficiency on the physical strain of these subjects can be shown by a simple calculation. When the PO remains the same (eg, 10.2W) and mechanical efficiency increases from 4.3% to 5.7%, the energy expenditure will be 237.21W and 178.92W, respectively. From energy expenditure the $\dot{V}O_2$ can be calculated, which is .68L/min and .51L/min, respectively (with an RER of 1.0). This calculation shows that an absolute increase of 1.4% in mechanical efficiency leads to a .17L/min decrease in $\dot{V}O_2$. The $\dot{V}O_{2max}$ of subjects with tetraplegia was on average 1.0L/min. Therefore, the increase in mechanical efficiency led to a 17% decrease in % $\dot{V}O_{2max}$ (from 68% to 51% $\dot{V}O_{2max}$) of the subjects who propelled their wheelchair. This is an important decrease in physical strain for these subjects, who often have a very low physical capacity.^{16,23} Therefore, it is of clinical importance to try to increase mechanical efficiency by improving, for example, the wheelchair design and a subject's propulsion technique and training status.

Differences in mechanical efficiency over time or between subjects are more visible when testing on higher (submaximal) PO levels. However, in our study, the PO had to be the same at all test occasions and had to be low, especially at t_1 , to include as many subjects as possible (meeting velocity criteria of mechanical efficiency and submaximal steady-state testing). The PO level could thus be optimal at t_1 but might be less perfect at t_2 or t_3 , and subsequently mechanical efficiency at t_2 and t_3 would be suboptimal.

A lack of a significant improvement in mechanical efficiency between t_2 and t_3 could be due to a reduced intensity or frequency of rehabilitation treatment. At the beginning of active rehabilitation, the focus could be on wheelchair skills and training. When a subject is able to move around independently, wheelchair training might not be the main focus. Especially between t_2 and t_3 , the intensity of the rehabilitation treatment may be less than optimal. In the Netherlands, subjects can be discharged earlier from rehabilitation if they do not have to wait until their housing has been made accessible. Although they still will be in a rehabilitation center, the treatment may no longer be very intensive. To induce physiologic training effects, training guidelines for this specific patient group should be available in rehabilitation centers. Furthermore, it is important to mention that the Dutch rehabilitation program for patients with SCI is fairly well standardized. All rehabilitation centers with a specialized SCI unit are organized under the Dutch-Flemish Society of Paraplegia and work toward a uniform rehabilitation protocol for people with an SCI.²⁹

Results of a study by Hjeltne and Wallberg-Henriksson³⁰ indicate that primary rehabilitation programs are likely to have

insufficient endurance training components for subjects with tetraplegia to improve their endurance capacity (as measured by $\dot{V}O_{2\max}$). Although muscle strength and activities of daily life (ADLs) improved during an intervention of 3 sessions of arm cycling training per week (for 16wk), this was not followed by an aerobic metabolic improvement.³⁰ Dallmeijer et al¹⁵ also found no significant increase in $\dot{V}O_{2\text{peak}}$ during a maximal exercise test on a wheelchair ergometer when testing at the beginning and end of active rehabilitation. On the other hand, maximal isometric strength, sprint PO, and maximal PO all improved significantly, together with the mechanical efficiency. They also found a decrease in performance time during a set of standardized ADL tasks. From these results and ours, it can be suggested that the improvement in mechanical efficiency in our study might have been due to functional improvement rather than aerobic metabolic improvement.

Future Studies

In this study, determinants for the course of mechanical efficiency during rehabilitation were limited to lesion characteristics, for example, level and completeness. As mentioned in the introduction, mechanical efficiency depends on the user's wheelchair skills, training status, and ergonomic fit to the wheelchair. Subjects used the same standardized wheelchair for each test occasion, which means that the increase in mechanical efficiency between t_1 and t_2 could not be dependent on an improvement in the wheelchair-user interface. In future, the relation between the course of wheelchair skills (eg, wheeling a figure of eight, a 15-m wheelchair sprint test) and training status (eg, PO_{\max} , $\dot{V}O_{2\max}$) with the course of mechanical efficiency will be investigated. If there is a relation between wheelchair skills or physical capacity and mechanical efficiency, that might be helpful information in writing more specific wheelchair training programs to improve mechanical efficiency during rehabilitation.

Clearly, the role of rehabilitation characteristics (ie, exercise training, intensity, form of exercise) needs to be studied.

CONCLUSIONS

The mean mechanical efficiency of wheelchair propulsion among study subjects improved significantly during the first 3 months of active SCI rehabilitation. After that, mechanical efficiency did not change significantly. It was significantly higher in subjects with paraplegia than in subjects with tetraplegia. Results for exercise block 2 showed that subjects with tetraplegia improved mechanical efficiency significantly more during the first 3 months of rehabilitation than did subjects with paraplegia. No differences were found between subjects with a complete or incomplete SCI.

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